

A Review of White Light Streamers at the End of Cycle 23

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Abstract. I give a brief review of the quiescent large scale visible corona with an emphasis on the origin, structure and role of streamers in the solar wind. The review is mostly based on results from the last 10 years of the SOHO mission and the goal is to provide a coherent picture of what is known on streamers at the end of the current cycle.

Keywords. Sun: activity, Sun: corona, Sun: magnetic fields, solar wind

This presentation is given on the occasion of a solar eclipse, one of the most spectacular natural phenomena on Earth. For ages, natural eclipses were the only way to observe with our own eyes the corona, the faint outer atmosphere of the sun. The aesthetic pleasure of the phenomenon aside, visible observations of the extended corona carry significant scientific value. In the last 200 years, numerous expeditions over the last 200 years have trekked into remote locations, fought against limited resources, unpredictable weather and capricious instrumentation to obtain a limited set of images over the few minutes that a total eclipse may last Zirker (1995).

But real progress in coronal physics requires long-term observations of the corona. Such observations have been made possible by specialized telescopes, called coronagraphs, that block the light from the solar disk creating an artificial eclipse. The LASCO coronagraphs Brueckner *et al.* 1995 aboard the SOHO mission have contributed significantly in our understanding of the corona over the last 10 years. We now know a great deal about the physics, morphology and evolution of the corona. It is impractical to summarize such extensive knowledge in such a short space. Interested readers can find much more information in dedicated textbooks (Golub & Pasachoff 1997; Aschwanden 2004). I will only give a brief overview of some key concepts of the large scale corona and describe what is known about the origins and structure of the building blocks of the corona, the white light streamers, and their role in the solar wind.

1. General Properties of the Large Scale Corona

Although the term “large scale corona” usually implies the visible corona, there exist several other “coronae” depending upon the mechanism responsible for their emission. The visible corona or *K-corona* is created by the reflection of the photospheric light by the coronal electrons through the Thomson scattering process. The same photospheric light is reflected by larger, dust particles to create the *F-corona*. The F-corona is usually a nuisance because it dominates the K-corona signal above a few solar radii without providing any information on coronal processes. The removal of the F-corona is an integral part for coronal analysis. Those interplanetary dust particles also radiate themselves in the infrared to form the *T-corona*. Finally, the coronal electrons can emit radiation at several spectral lines, from X-rays to the infrared, but this so-called *E-corona* becomes

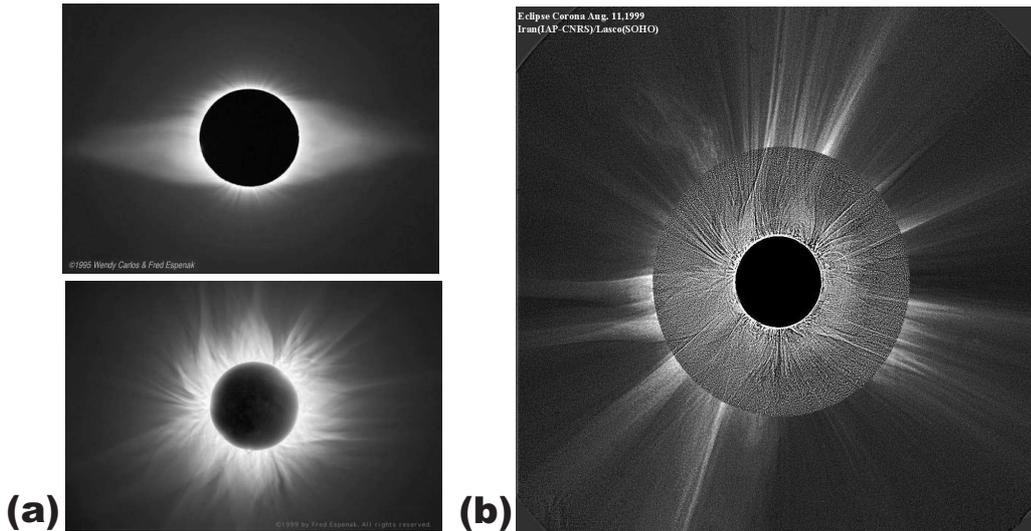


Figure 1. (a) Views of the large scale corona during solar minimum (top) and maximum (bottom) obtained during natural eclipses (courtesy of F. Espeniak). (b) Composite of images taken during the Aug, 11, 1999 eclipse. The inner image has been edge enhanced to reveal the fine structures. The outer image is taken by LASCO/C2 (courtesy of S. Koutchmy)

extremely weak within a couple of radii above the surface. Here I focus only on visible light (K-corona) observations.

Because the coronal signal is just a reflection of the bright photospheric light, it is several orders of magnitude weaker than brightness of the solar disk. For this reason it is visible when the sun is eclipsed. Atmospheric scattering limits the height to which the corona is detected to about $3 R_{sun}$. The best observations are obtained from space where the coronal signal is detectable out to $30 R_{sun}$ or more. Coronagraphs have been flown in sounding rockets since the 60s and on satellites since the 70s. The latest such instruments are the LASCO coronagraphs which observe the corona from 1 to $32 R_{sun}$ continuously since early 1996. A new set of coronagraphs and heliospheric imagers, called SECCHI Howard *et al.* 2002, will soon be launched aboard the STEREO mission.

There are two methods of coronal observations. The first records the polarized brightness (pB) of the corona by obtaining observations through a set of polarizers in 3 or 4 different angles and then summing the resulting images appropriately Billings 1996. This technique has been used traditionally by ground-based instruments because it removes the contributions of the F-corona and the sky background which are both unpolarized at heights below a few R_{sun} . However, this technique also removes the unpolarized part of the K-corona and is insensitive to coronal structures at large angles from the limb due to the angular dependence of the pB intensity Vourlidas *et al.* 2000. For space-based observations, there is no need to resort to pB observations; there is no sky background signal to remove and the F-corona is polarized above about $5 R_{sun}$. The majority of the LASCO observations are total brightness observations which record a larger portion of the coronal brightness and are much more sensitive than pB observations to structures away from the solar limb. For this reason, total brightness observations can detect the faint coronal mass ejections along the Sun-Earth line.

One of the fascinating aspects of coronal observations is its changing morphology with time. It varies from a relatively simple disk seen edge-on during solar minimum

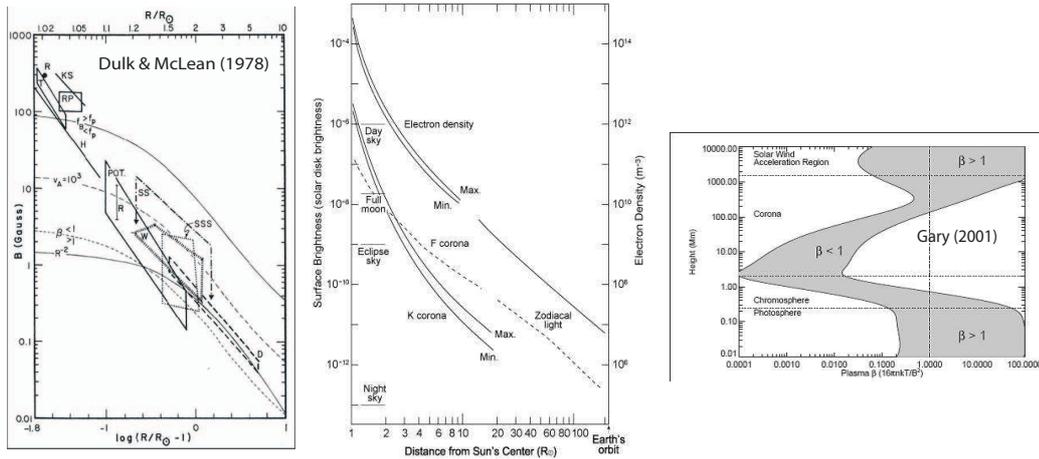


Figure 2. Plots of the magnetic field (left), electron density (right), and plasma β (bottom) as a function of height for typical coronal conditions.

to a bewildering collection of ray structures all around the disk during solar maximum (Figure 1a).

Electron densities can be directly extracted from coronagraph observations of the quiet corona. Historically, they are estimated from the inversion of the equations that relate the electron density to the polarized brightness van der Hulst 1950 for the simple reason that are easier to invert. But pB observations from space are costly (in terms of on-board resources) to obtain and provide less information compared to total brightness observations as we have discussed already. On the other hand, there has been no way to access the density information in the large number of available total brightness observations from LASCO. The situation has changed recently. Hayes, Vourlidas & Howard (2001) demonstrated a technique for the inversion of total brightness observations with very good results. However, both inversion techniques rely on the assumptions of axisymmetric coronal density. This is a rather simplistic assumption about the true 3D structure of the corona, especially during solar maximum. More sophisticated approaches to derive the density of coronal structures have appeared over the last few years. Frazin (2000) has demonstrated a tomographic technique for reconstructing the density from a time series of coronal observations and Thernisien & Howard (2006) have developed a forward modeling technique that fits various structures (e.g., a streamer, a flux-rope) to observations and estimates the electron density based on a minimization scheme.

Besides the electron density coronal physics are also controlled by the magnetic field. Both density and magnetic field vary during the course of the solar cycle and from active regions to quiet sun areas. The typical variation and magnitude of these quantities, is shown in figure 2. A more interesting quantity is the ratio, β , of the plasma pressure to the magnetic pressure, which reveals the relative importance of magnetic to plasma processes. This ratio is also shown in figure 2. The interplay between magnetic field and coronal plasma can be seen in the changing morphology of the corona with increasing distance from the surface. Figure 1b is a composite of an inner corona image taken during the eclipse of August 11, 1999 and of the outer corona image taken with the LASCO/C2 coronagraph. The inner coronal image has been edge-enhanced to reveal fine features and shows that closed structures dominate whereas the outer corona consists of only filamentary or ray-like structures. As we'll see later, this morphology reflects the transition from closed to open field regions.

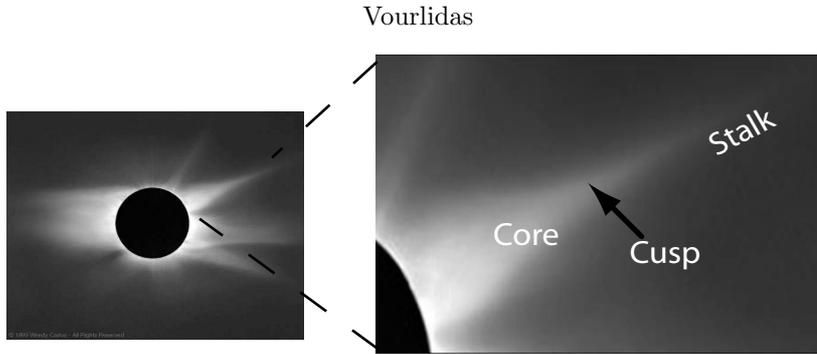


Figure 3. Definition of a streamer and other commonly used terms.

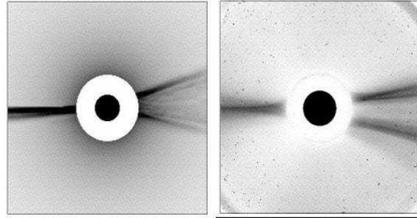


Figure 4. Comparison of streamer simulation (left) to LASCO observation (right) (Wang et al. 1997).

2. What are the streamers?

Our brief introduction to white light coronal physics has not addressed yet a rather important question: where does the structure of the corona come from? First we need to define some of the common terms used in the field. Figure 3 shows the various features on a typical coronal streamer. The corona consists of helmet-like structures, the *streamers*, that progressively thin out to a single ray, or *stalk*. The location where the streamer transitions from a bulge to the stalk is called the *streamer cusp*. The *core* of the streamer is the inner part of the streamer under the cusp. Since the coronal appearance depends on the magnetic solar cycle, it is natural to assume that the streamer morphology is also influenced by the large scale magnetic field of the sun. Early on, Howard & Koomen proposed that the heliospheric current sheet could be an extension of the low corona streamer structure. Subsequent work has verified the connection between streamers and the neutral surfaces of the large scale solar magnetic field (see also van Driel-Gesztelyi (2006)).

For example, Wang *et al.* (1997), Wang, Sheeley & Rich (2000) have modeled the streamers as locations of bends of the magnetic current sheet. The magnetic field was extrapolated using the source surface model under the assumption that the source surface was located at a height of $\sim 2.5 R_{sun}$ Wang & Shhley 1992. They assumed a plasma sheet of thickness of 3-5 $^\circ$ around the magnetic current sheet. The brightness of these structures was then calculated via the standard Thomson scattering equations. As can be seen in figure 4, the simulation reproduces very well the appearance of the corona in the LASCO images. A compact view of the corona is given by synoptic or Carrington maps (see http://lasco-www.nrl.navy.mil/carr_map/agu2000.htm for details and examples). These maps are essentially 360 $^\circ$ slices of the corona at a given height put together in reverse time sequence. They offer an easy way to follow the coronal evolutions at different heights. When we compare synoptic maps of the current sheet and the visible corona, the relation between the two becomes obvious (Figure 5). As the solar cycle progresses,

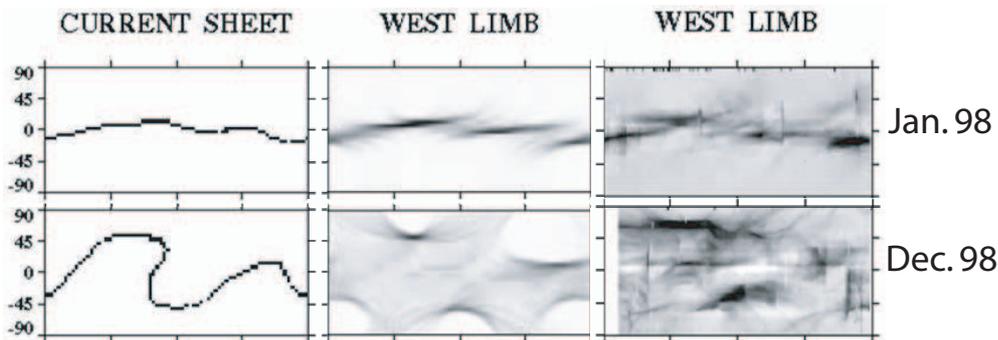


Figure 5. Evolution of the current sheet (left) and streamer structure (right) during the ascending phase of cycle 23. The middle panel shows the simulated corona. The difference between the simulations and the observations can be attributed to the rapid photospheric changes that are not captured by synoptic magnetic field observations (from Wang et al. 2000).

the shape of the current sheet becomes more twisted and the streamers increase in numbers. Some of the observed complexity is missing from the simulated results (Fig. 5). The global photospheric magnetic field is the lower boundary for the coronal magnetic field extrapolations that determine the shape of the current sheet. Since, magnetograph observations are only possible on the visible part of the disk, the backside magnetic field must be extrapolated from synoptic observations over a whole rotation (~ 27 days). We have to assume that the photosphere does not change over a solar rotation. While this is more or less true during solar minimum, it is increasingly wrong as the cycle ascends. For this reason, global magnetic field extrapolations cannot capture magnetic changes that occur over the course of a few hours or even days and the resulting streamer predictions start to deviate from the observations in detail. The large scale structure, however, is well represented by this model in all phases of the cycle. These simulations would improve if magnetic field measurements over a large area of the solar surface become available.

However, one can go the other way and use the white light observations to correct the magnetic field extrapolations. Saez *et al.* (2005) have followed this approach by introducing additional features on the predicted current sheet to match the LASCO synoptic maps. Next they showed that these photospheric field corrections were not arbitrary but corresponded to coronal features seen in EUV maps.

3. Small Scale Streamer Structure

An inspection of Figure 4 shows significant small scale structure within the streamers when they are seen face-on. A new forward-modeling technique developed recently at NRL was used to model this fine scale structure successfully Thernisien & Howard (2006). The derived electron density profiles suggest that the interstreamer density variation could be as much as a factor of 10! No satisfactory explanation for this effect has been proposed so far.

Filamentary structures low in the corona (below $2-3 R_{sun}$) are nothing new. Careful analysis of eclipse observations by Koutchmy *et al.* (1994) has revealed threads with subarcsecond widths (i.e., a few hundred kms). These threads seem to be short-lived (lifetimes of 100s - 1hr) and some correlate well with rays seen in LASCO-C2 (Figure 1b). It is not yet clear what determines the small scales of these threads, and whether they are flows (or electron streams) at streamer boundaries or from spicules or from something else. It is plausible that some of the threads could be the white light counterparts of

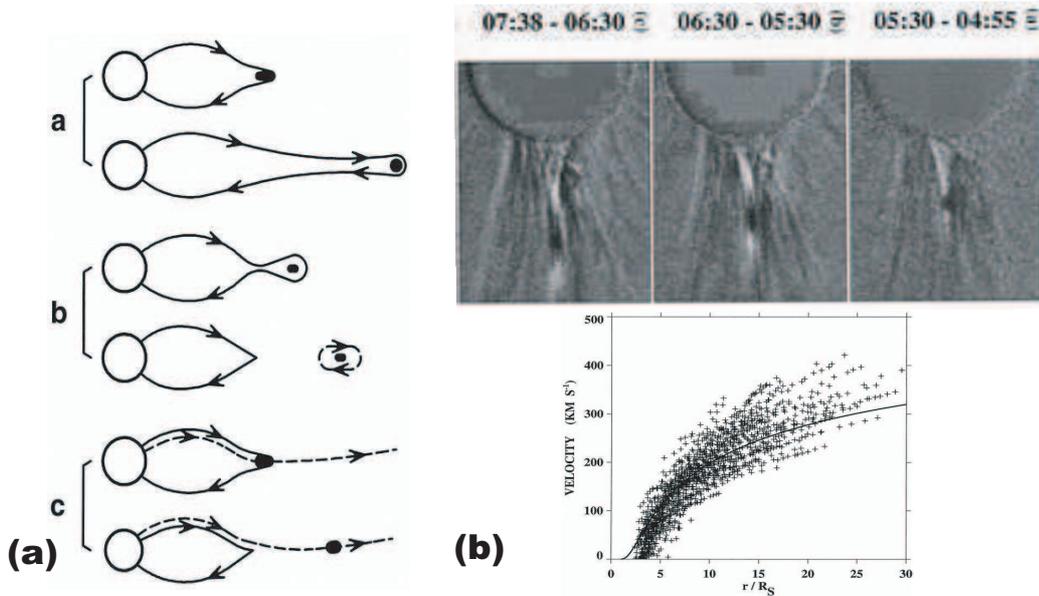


Figure 6. (a) Mechanisms for ejecting plasma from closed loops to the plasma sheet. (a) the plasma pressure overtakes the magnetic pressure and stretches the loop to infinity creating new open flux. (b) Reconnection at the loop top creates a new plasmoid. In a 3D configuration, this process creates a fluxrope with its ends attached to the sun. (c) Reconnection between a neighboring open field line and a closed loop ejects plasma along the open field line. In a 3D configuration, this process corresponds to footpoint exchange and no new open flux is created. (b) A typical white light blob observed in LASCOSCOPE running difference images. Measurements of a large number of them agree with slow solar wind velocity profiles (from Wang *et al.* (2000)).

type-III radio bursts (Koutchmy 2004) but not all. To solve this mystery we need long-term, extremely high-resolution observations of the inner corona. Unfortunately no such mission is being implemented or planned for the near future.

Another population of extremely fine-scale coronal threads has been observed but this time at large distances from the sun ($\sim 20 - 30 R_{sun}$). Woo & Habbal (1999) using radio scintillation experiments detected small scale density variations of the order of 20 km at $20-30 R_{sun}$, which they attributed to coronal thread-like structures. These threads are assumed to trace open field lines from the quiet sun, to be ubiquitous and long-lasting (Woo 2005, 2006). However, none of these structures has been traced down to the surface and is very difficult to explain how long-lived open field lines can extend radially from the surface to $30 R_{sun}$. Also, the plasma β is becoming significant at such large distances from the surface and the electrons do not necessarily follow field lines. However, the existence of such fine structures in the solar wind and their relation to the inner corona threads and ultimately to the solar magnetic field is an intriguing mystery.

4. Streamers and the Solar Wind

We know that under the streamer cusp, the loops are closed and their plasma should be confined there. At the same time the streamer stalks are bright extending to large distances into the heliosphere. Where does this plasma come from? Figure 6 shows three possible ways that plasma from a closed loop can be ejected into the plasma sheet (Wang *et al.* 2000). Although all three processes are likely in the corona, only the reconnection with open field lines at the streamer boundary does not destroy the streamer and must

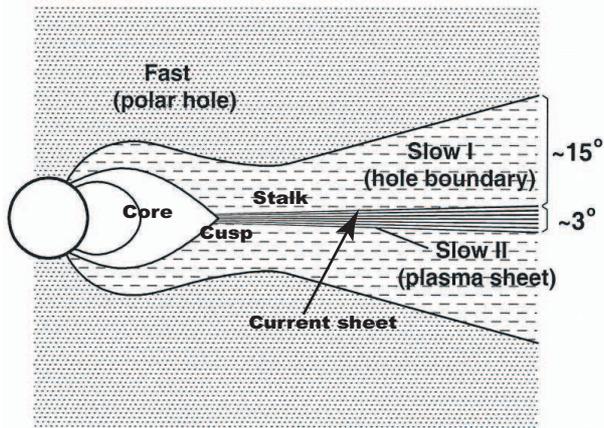


Figure 7. A graphical summary of our current understanding of the morphology of streamers and their role in the generation of solar wind (Adapted from Wang *et al.* (2000)).

be the dominant one. In that case, we should expect significant flows at the streamer boundaries. Indeed, one of the first observations from UVCS has shown a depletion of O VI at the streamer core relative to the its boundaries (Kohl *et al.* 1997). The effect can be explained by gravitational settling of O VI in the closed loops, at the streamer core (Noci *et al.* (1997), Raymond *et al.* (1997)), which implies that the plasma at the streamer boundaries is in motion.

Reconnection and flows at streamer boundaries are also invoked by MHD models of the slow solar wind (Einaudi *et al.* (1999), Karpen & Dahlburg (1997)). The models predict that the velocity shear between the plasma near the current sheet relative to the plasma at the boundary will lead to MHD instabilities which in turn will give rise to turbulent eddies and plasmoids. This is exactly what has been observed with LASCO (Sheeley *et al.* (1997), Wang *et al.* (2000)) as moving blobs along streamer stalks. Figure 6b shows an example of a typical LASCO blob and velocity measurements of a large number of them from Wang *et al.* (2000).

5. Conclusions

The goal of this short review is to focus on those physical problems of the visible corona where considerable progress was made over the last decade. As the current cycle draws to an end and the next cycle begins with the availability of a fresh set of instruments (STEREO, SDO) and a completely new mission concept (STEREO), it is useful to reflect on what we know and what questions we might be able to answer in the future. Our discussion can be summarized as follows:

- Streamers are Thomson scattered photospheric light by electrons located on folds of the large scale current sheet. The plasma sheet thickness is only 3-5° wide.
- The streamers have significant fine structure and observations both in the inner and outer corona are suggestive of the existence of scales smaller than a couple 100 Kms.
- The plasma sheet is created by continuous ejection of plasma via reconnection at the boundaries of the streamer.
- The slow solar wind seems to be generated by these plasma flows.

These conclusions leave several questions unanswered:

- Where does the small scale streamer structure come from?
- What is the true extent of streamers?

- What is the density structure within the streamers?
- How far do streamers extend? Can we see their imprints at 1 AU?

Finally, figure 7 summarizes, in a graphical form, our discussion on the relation of white light streamers to the large scale magnetic field and the origin of the solar wind.

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Discussion

COLLEAGUE: question

VOURLIDAS: Indeed,.